# 3D FABRICATION BY MOVING MASK DEEP X-RAY LITHOGRAPHY ($M^2DXL$) WITH MULTIPLE STAGES

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## ABSTRACT

The final goal of this study is to establish a technology to realize 3-dimensional (3D) microstructures with free shaped wall by synchrotron radiated deep X-ray lithography. In this paper, we presented two important advancements toward the goal. (1) A reverse approach using Fourier transformation technique to define the optimum X-ray mask movement pattern was improved and applied to a V-grooved microstructure fabrication. (2) A new X-ray exposure system that combines moving mask deep X-ray lithography technique ($M^2DXL$) and multiple stages was developed and the system performance was confirmed.

## INTRODUCTION

Recently, high aspect ratio 3-dimensional (3D) microstructures have been widely applied to various MEMS. Deep X-ray lithography is a very promising technology to realize the high aspect ratio microstructures due to features of the X-ray such as short wavelength and small divergence of the beam. By combining the deep X-ray lithography with subsequent electroplating and molding technique, replication of the fabricated high aspect ratio microstructures by various materials such as plastic, metal, and ceramics becomes possible. This process has been known as a LIGA process.

However, a conventional deep X-ray lithography was good at fabricating microstructures with vertical wall but has very limited controllability for cross-sectional shape of microstructures. In order to apply the deep X-ray lithography to various fields such as micro-sensors, micro-actuators and MEMS devices, more flexible and precise controllability for the cross-sectional shape of microstructures has been demanded. To meet these requirements, we proposed a moving mask deep X-ray lithography technique ($M^2DXL$) shown in Fig. 1. The validity of this technique has been demonstrated by fabricating various microstructures [**1-4**].

With respect to the establishment of this technology, there are two aspects to be addressed. One aspect is a procedure to define an optimum mask pattern and its movement, the other is a stage system to realize more complex exposure sequence. In this paper, we present approaches toward these two aspects.

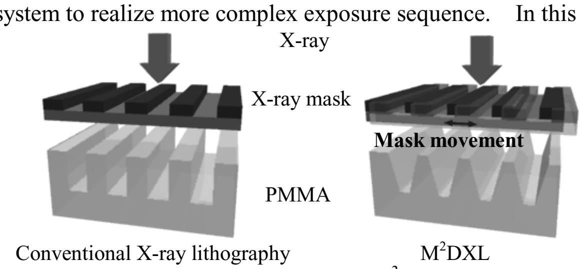


*Figure 1. Concept of the $M^2DXL$.*

In the $M^2DXL$ technique, the cross-sectional shape of a microstructure is defined by controlling the exposed energy over a resist by controlling a movement pattern namely trajectory and velocity of an X-ray mask movement. Therefore, when a target microstructure is given, both of these two patterns should be designed based on the plane and the cross-sectional shape of the target structure.

Formerly, a mask pattern and its movement pattern were determined by a try and error method using a program developed to predict a shape of a microstructure from a given mask pattern and its movement pattern as follows. The program calculates an exposed energy distribution over a resist using a mask pattern and its movement pattern, then convert this calculated exposed energy distribution to a 3D microstructure shape using pre-measured non-linear relationship between exposed energy and processed depth. First, simple X-ray mask patterns such as a line and space (L/S) pattern or a circular window array pattern were defined empirically according to a target shape. Then a certain movement pattern of the mask was assumed and the final shape was predicted using this program. The predicted shape was compared with the target shape and the pre-determined movement pattern is modified based on the results. This procedure is repeated several times until the optimum movement pattern was obtained. When the predicted cross-sectional shape corresponds with that of the target pattern, the inputted mask movement pattern was determined as the optimum mask movement pattern. We call this approach as a "Forward approach". The major drawback of this forward approach is that it needs empirical modification step of the mask movement pattern and this make it difficult to computerize the whole step including the optimization of a mask pattern.

To overcome this drawback, we proposed an "Inverse approach" for theoretical determination of an optimum mask movement pattern using Fourier transformation technique [**4**]. However, this technique met difficulty when it was applied to the fabrication of a V-groove structure. In the first part of this paper, we present the modified inverse approach to solve this problem.

Another approach to realize more complex exposure for 3D fabrication is the improvement of an exposure system. A sidewall inclination of microstructures fabricated by only $M^2DXL$ was limited to an angle of less than 90°, namely overhanged structure is impossible to realize. To realize the sidewall angle of over 90°, inclined exposure is one promising approach [**5**]. Therefore, we developed a new powerful X-ray exposure system with multi stages shown in Fig. 2 that enable us to realize combined exposure of inclined and $M^2DXL$ to fabricate free shaped 3D microstructures with controllable inclined, curved and vertical wall [**6**].

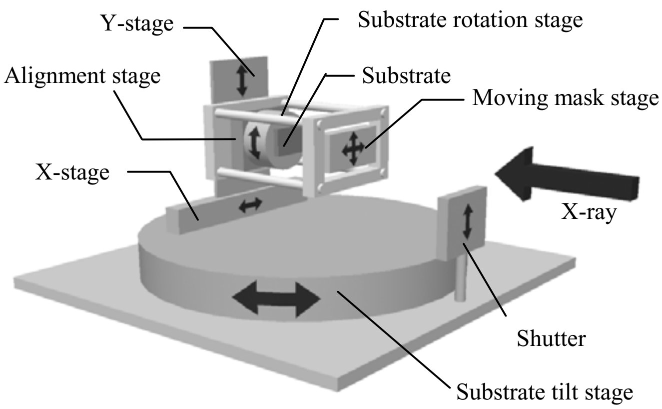


*Figure 2. Configuration of the newly developed deep X-ray lithography system with multiple stages.*

In the last part of this paper, we present the results of 3D microfabrication realized by newly developed X-ray exposure system with multiple stages.

## INVERSE APPROACH

An algorithm of the inverse approach using Fourier transformation technique requires an X-ray mask pattern and a target cross-sectional shape for input data. For simplification, the target microstructure was assumed in 2-dimensional space, namely a cross section is identical at any position along y axis. The results can easily expanded in real 3-demensional space. A V-groove microstructure that has 40µm pitch and 20µm depth was adopted as a target shape. A function *T(x)* define the depth of target from a resist surface at position *x*. The X-ray mask pattern used was 20/20 µm L/S. A function *M(x)* define the X-ray mask pattern and it was defined as 1 (transparent) or 0 (non-transparent) at position *x*. These functions *T(x)* and *M(x)* are shown in Fig. 3. The pre-measured relationship between exposed energy and processed resist depth was shown in Fig.4. At this measurement, PMMA was used as an X-ray resist material and exposed at 1 atm He atmosphere. The development has been carried out using GG developer at 39 ºC for 120 min.

Using this relationship, *T(x)* was transformed to function *E(x)* that defines exposed energy distribution to obtain the target shape at position *x*. A function *e(x)* defines exposed energy when the mask moves by distance *x*, namely *e(x)* corresponds to the mask movement pattern. Using *M(x)* and *e(x)*, *E(x)* is given by the following formula:

$$E(x) = \int M(x-\tau)\, e(\tau)\, d\tau \qquad (1)$$

By applying Fourier transformation technique, *E(x)*, *M(x)* and *e(x)* were transformed to *E(f)*, *M(f)* and *e(f)*, and subsequently Eq. (2) right hand side was derived.

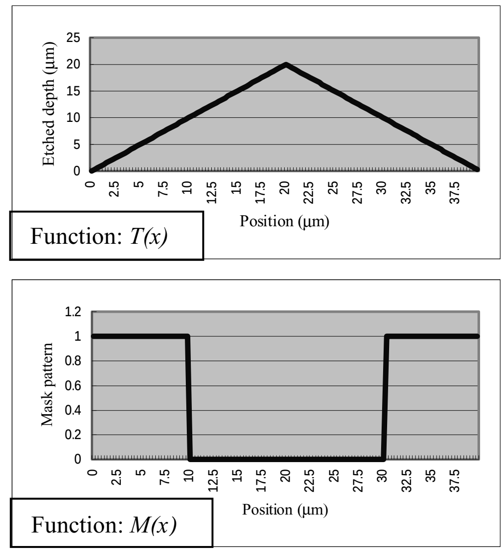


*Figure 3. Functions corresponding to the cross-sectional shape of the target microstructure and the X-ray mask pattern.*

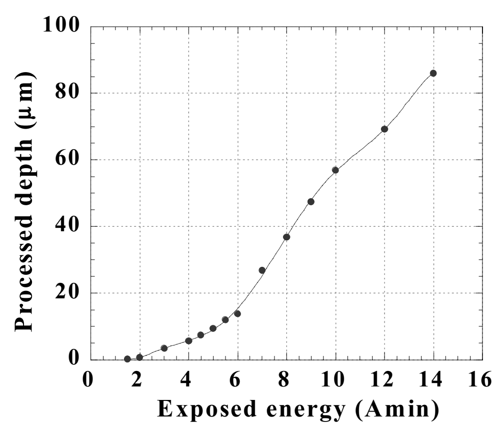


*Figure 4. Relationship between exposed energy and processed depth.*

$$E(f) = M(f)\, e(f) \quad \Rightarrow \quad e(f) = E(f)\, /\, M(f) \qquad (2)$$

By applying inverse Fourier transformation technique to *e(f)*, the exposed energy *e(x)* was obtained as shown in Fig. 5. Notes that the *e(x)* had negative value and this indicated that it was impossible to fabricate the target shape theoretically. Since the target shape is not allowed to change, the processed depth was added to the target shape. The Eq.(2) calculated repeatedly by adding the depth by 0.1 µm to *T(x)* until the calculated *e(x)* didn't have negative value. Finally, non-negative exposed energy pattern was obtained by adding 12.5 µm to the original target shape. The *e(x)* corresponding to this *T(x)*+ 12.5 µm was written as $e_{12.5}(x)$ and shown in Fig. 6.

The cross-section of the fabricated microstructure using $e_{12.5}(x)$ is shown in Fig. 7 and measured depth was shown in Table 1 with the target depth. The cross-section of the fabricated microstructure

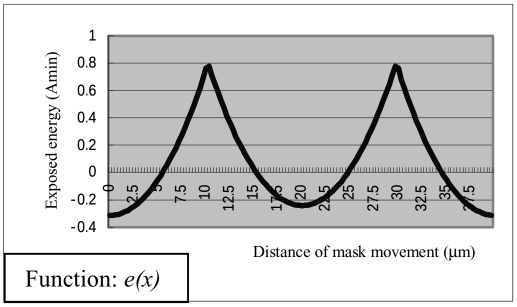


*Figure 5. Mask movement pattern e(x) obtained from T(x) and M(x).*

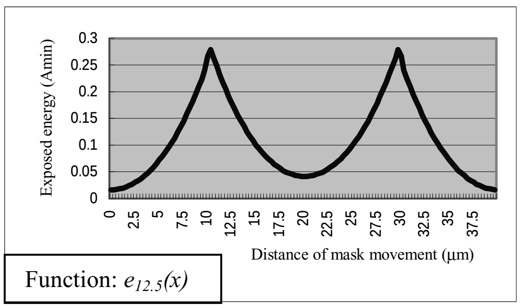


*Figure 6. Mask movement pattern $e_{12.5}(x)$ from T(x)+12.5 and M(x).*

was different from that of the target shape. To solve this discrepancy between the target and fabricated cross-section; (1) the exposed energy $E_T$ and $E_M$ correspond to the target depth and measured depth, and their ratio $E_T / E_M$ were calculated, (2) the corrected exposed energy distribution *Ec(x)* was calculated by multiplying $E_T / E_M$ with *E(x)* as shown in Fig. 8, (3) $e_{c12.5}(x)$ shown in Fig. 9 was calculated based on the previously described procedure. The cross-section of the fabricated microstructure is shown in Fig. 10.

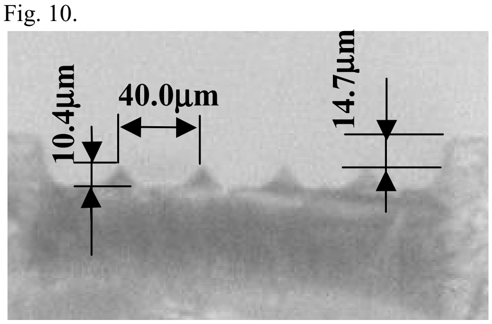


*Figure 7. Cross-section of the fabricated microstructure.*

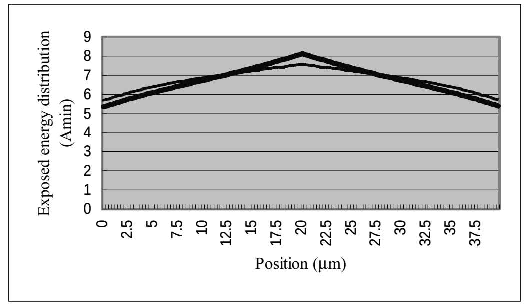


*Figure 8. Exposed energy distribution. The thin line is the original E(x), and the thick line is the corrected $E_C(x)$.*

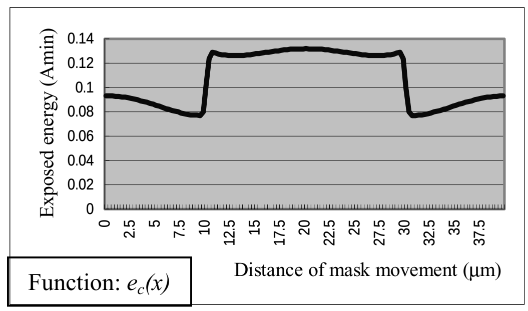


*Figure 9. Corrected mask movement pattern $e_c(x)$.*

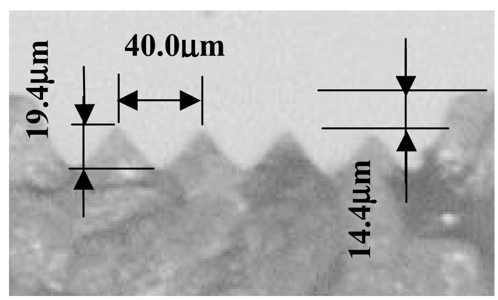


*Figure 10. Cross-section of the fabricated microstructure by correcting the exposed energy distribution.*

As a result, the cross-sectional shape of the V-shaped groove was close to the target shape was realized. One possible explanation of the existence of $E_T / E_M$ is the effect of intermittent exposure we reported by previous paper [4]. The inverse approach that takes into this effect is now under developing.

*Table 1. Comparison of the target microstructure and fabricated microstructure.*

| *Position (μm)* | *Target depth (μm)* | *Measured depth (μm)* | *Calculated exposed energy for the target depth $E_T$ (Amin)* | *Calculated exposed energy for the measured depth $E_M$ (Amin)* | *Exposed energy ratio between required and measured $E_T / E_M$* |
|---|---|---|---|---|---|
| *0* | *12.5* | *14.7* | *5.69* | *6.02* | *0.94* |
| *5* | *17.5* | *20.8* | *6.39* | *6.72* | *0.95* |
| *10* | *22.5* | *24.3* | *6.87* | *7.01* | *0.98* |
| *15* | *27.5* | *25.1* | *7.23* | *7.06* | *1.02* |
| *20* | *32.5* | *25.1* | *7.56* | *7.06* | *1.07* |

## NEW EXPOSURE SYSTEM

A newly developed exposure system shown in Fig. 2 has 6 stages; a substrate rotation of ±180° and a substrate tilting of ±90° to control the incident X-ray angle in any direction to the substrate, an X and a Y stages used to expose the substrate with maximum size of 80 x 55 ($mm^2$), an X-Y alignment stage to align the substrate with an X-ray mask by 5 µm resolution, and the X-Y stage for the X-ray mask movement that can be moved against the substrate in X-Y plane with stroke of 80 µm and resolution of 10 nm.

## APPLICATIONS OF THE EXPOSURE SYSTEM

Figure 11 shows the fabricated microstructure using the newly developed exposure system. The moving mask stage and triangular X-ray mask with different pattern height were used. The mask was moved with amplitude of 50 µm with constant speed. The exposed energy was set to 10 Amin. As a result, the grating pattern with different pitch was fabricated as shown in Fig. 11.

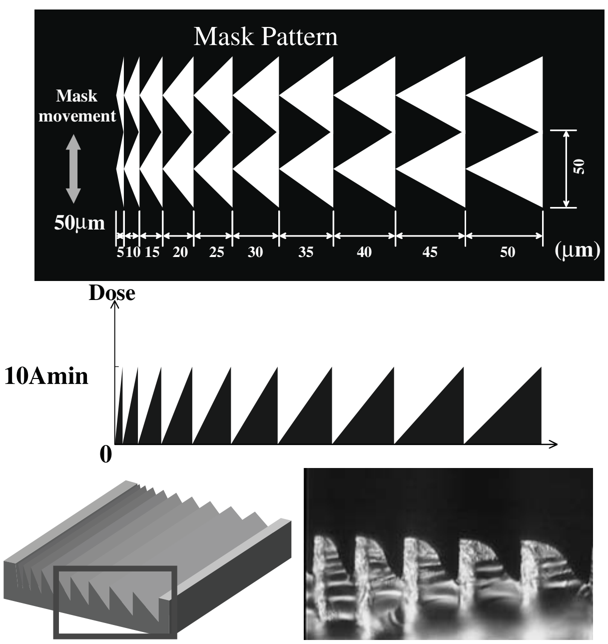


*Figure 11. Photograph of the fabricated grating pattern with different pitch by the $M^2$DXL.*

Figure 12 demonstrates the combination exposure of inclined exposure and $M^2$DXL using the moving mask stage and the substrate tilting stage. The mask with L/S (50/50, 50/20µm) pattern was utilized. By $M^2$DXL with movement amplitude of 40 µm and constant speed, a microstructure shown in Fig.12-B was fabricated. By inclined exposure of 45°, microstructure shown in Fig. 12-C was fabricated. Fig. 12-D shows the result of combined exposure of inclination and $M^2$DXL. Inclined sharp teeth were realized as expected. In order to realize the target 3D microstructure using this system, the exposure procedure including tilting and rotation should be optimized. Therefore, a need for optimization procedure using theoretical method becomes more important.

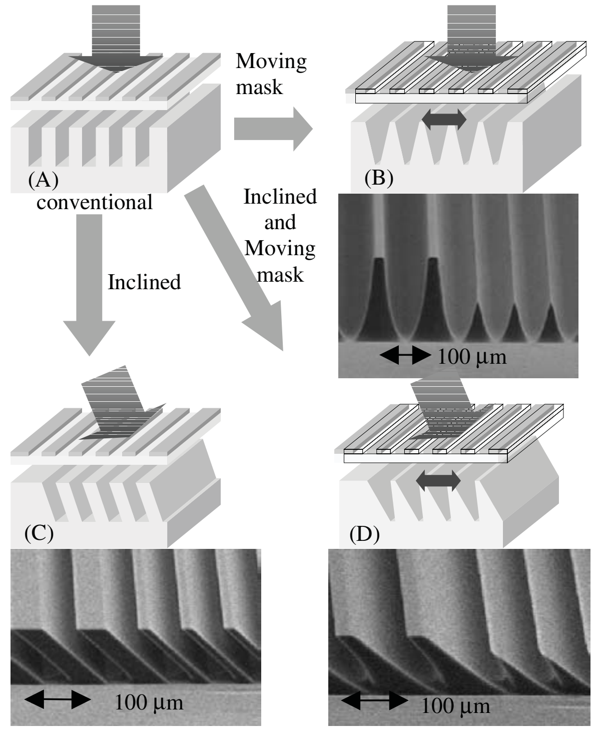


*Figure 12. SEM photographs of moving mask, inclined and combination exposure.*

## CONCLUSION

Two important advancements, the algorithm called "Inverse approach" and the newly developed exposure system with 6 stages was presented. The optimum mask movement trajectory was decided by the inverse approach and the V-groove microstructure with 40µm pitch and 20µm depth was fabricated successfully. The new exposure system enables to have more functions such as moving mask exposure, substrate inclined exposure, and substrate rotation exposure. All these exposure can be combined freely. The applications of the new exposure system were demonstrated. These advancements will enlarge the application field of deep X-ray lithography.


### REFERENCE

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